A study of a monodisperse microbubble jet under microgravity conditions

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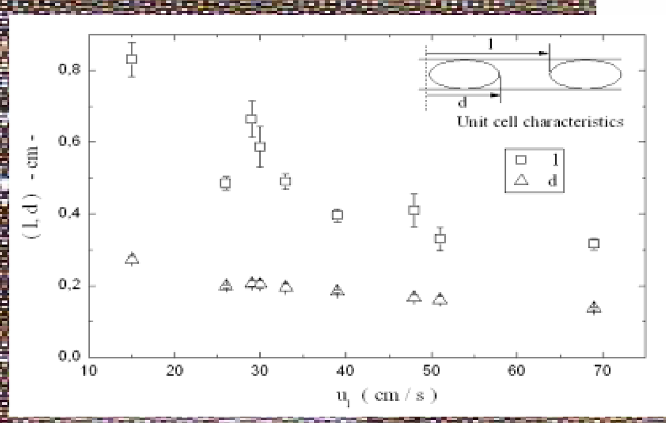
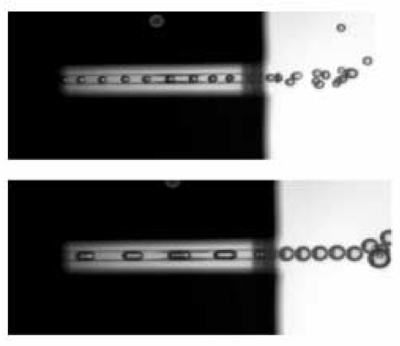
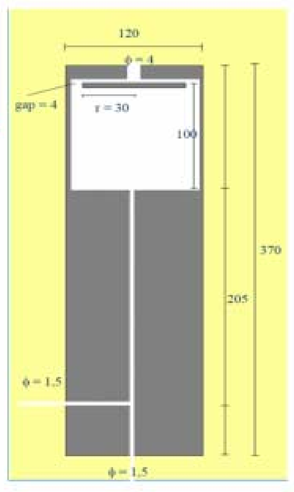
I.- A novel injector concept has been developed and characterized in which a slug flow is pre-generated in a capillary T-junction before injection. The injector operating mode is dominated by capillary forces, so it is insensitive to gravity level. The performance of the injector system has been tested in a series of drops in the ESA's Zarm drop tower facility. Experimental results show the generation of a virtually monodisperse jet of bubbles, of sizes of the order of employed capillary tube, and indeed independent of gravity. Statistical data on bubble sizes, and on the dispersion of bubbles in a cavity, have been recorded. Events of coalescence of injected bubbles have been observed, but these appear to have small statistical relevance. All these results are the basis for a coming new series of parabolic flight experiments.



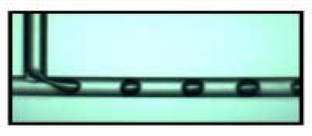
The concept of the composite injector

Key idea:
Form the bubbles prior to injection ('slug flow')
Form bubbles by capillary forces at T-junction





Theory of bubble detachment I: force balance



The bubble breakup is produced when cross-flow drag forces balance capillary forces

It is independent of gravity!

Works nominally at SMALL Weber number! $We = \frac{\rho u^2 d}{\sigma}$

Drag force: $F_D = C\rho_l(u^*)^2 d_B^2$

Capillary force: $F_\sigma = \pi\sigma d_g f$

$$\eta = \frac{d_g}{d_l} \qquad \xi = \frac{d_B}{d_l}$$

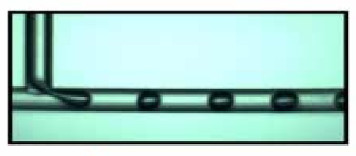
$$We^* = We^0 \frac{\xi}{(1-(\alpha\xi)^2)^2}$$ Effective Weber number (conservation)

$$We^* \frac{\xi}{\eta} = We^c$$ Detachment condition

$$\epsilon = \left(\frac{We^0}{\eta We^c}\right)^{1/2}$$

$$\boxed{\xi = \frac{1}{\alpha}\left(1+\frac{\epsilon^2}{4\alpha^2}\right)^{1/2} - \frac{\epsilon}{2\alpha^2}}$$

Theory of bubble detachment II: size and dispersion



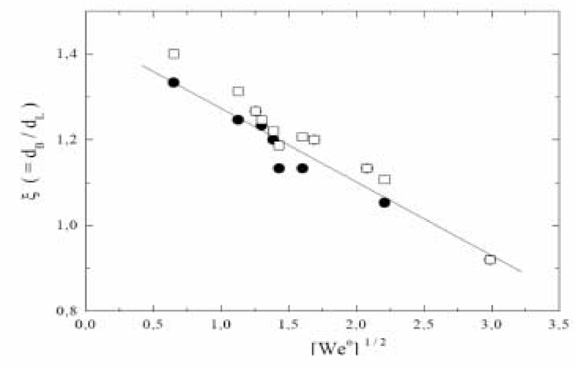
Prediction for dimensionless bubble size:
- Order one (major improvement!)
- Weak dependence of We
- Reduced size dispersion

$$\boxed{\xi = \frac{d_B}{d_l} = \frac{1}{\alpha} - \frac{1}{2\alpha^2}\left(\frac{We^0}{\eta We^c}\right)^{1/2} + \mathcal{O}(\epsilon^2)}$$

Size dispersion: the same small parameter controls the 'noise reduction':

$$\boxed{\frac{\delta d_B}{d_B} = \frac{\delta\xi}{\xi} = \frac{\epsilon}{4\alpha}\frac{\delta We^c}{We^c} + \mathcal{O}(\epsilon^2)}$$

Comparison with experiments (1g and 0g)

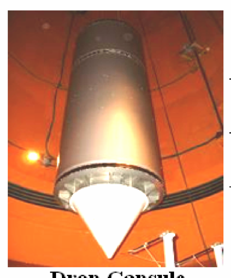


Excellent agreement with theory

Insensitivity to gravity

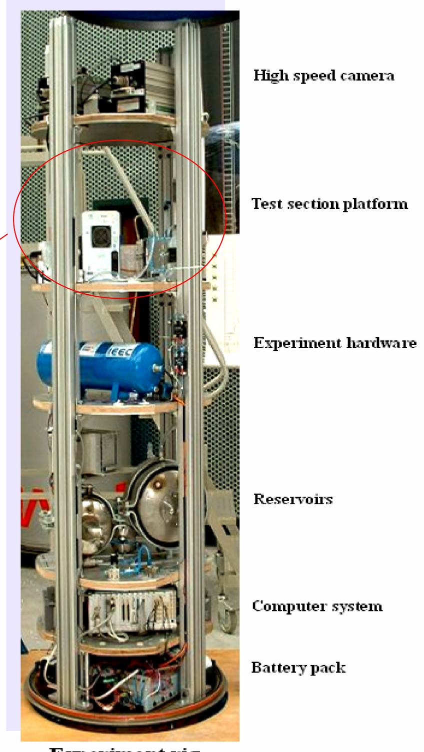
Bubble size is fixed essentially by capillary diameter

ZARM Drop Tower experiments : the cavity flow



Drop Capsule

-Pressure environment
p = 1.013 hPa
-Thermal environment
temp = 25° C
-Controlled deceleration



Experiment rig

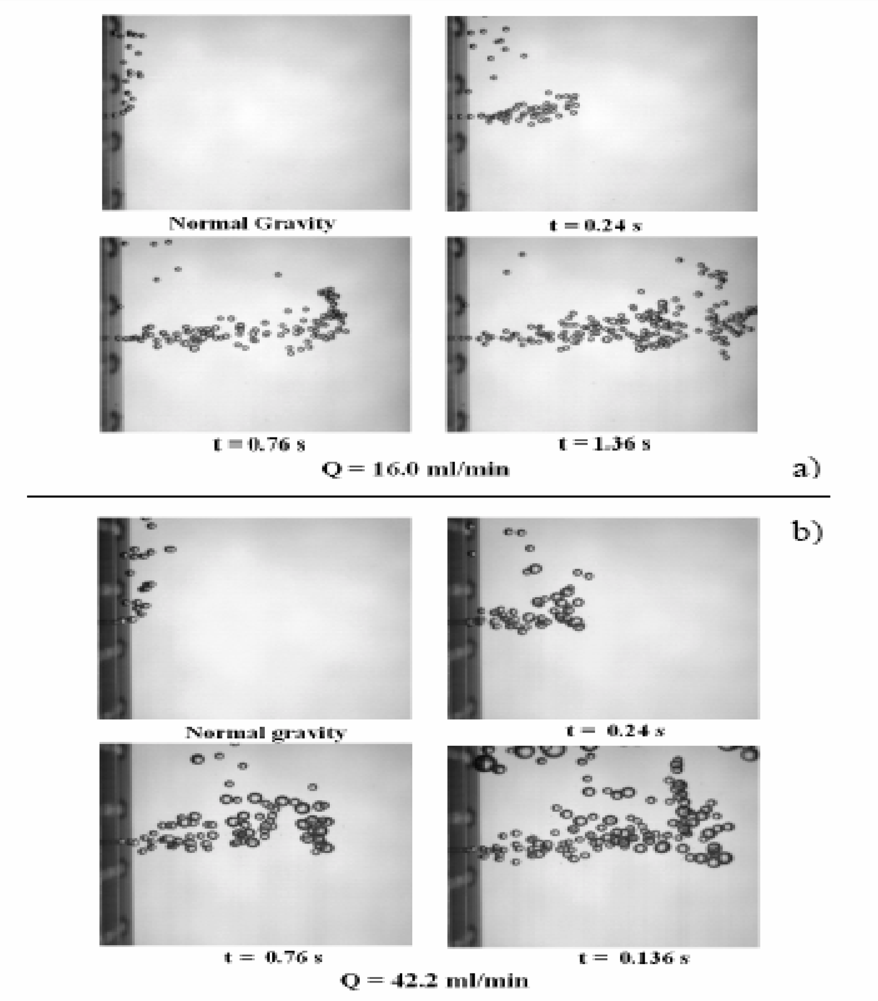
Experimental program:

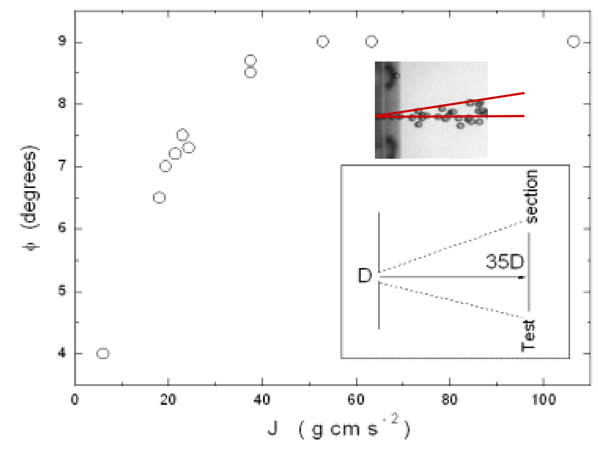
Drop (n)	Q_l (ml / s)	Q_g (ml / s)	u_l (m / s)	u_g (m / s)
1	0.69	0.27	0.39	0.15
2	0.69	0.27	0.39	0.15
3	1.23	0.30	0.69	0.17
4	0.45	0.26	0.26	0.09
5	0.91	0.32	0.51	0.18
6	0.58	0.16	0.33	0.09
7	0.26	0.15	0.15	0.08
8	0.51	0.16	0.29	0.09
9	0.85	0.25	0.48	0.14
19	0.52	0.21	0.29	0.12
11	0.54	0.21	0.30	0.12

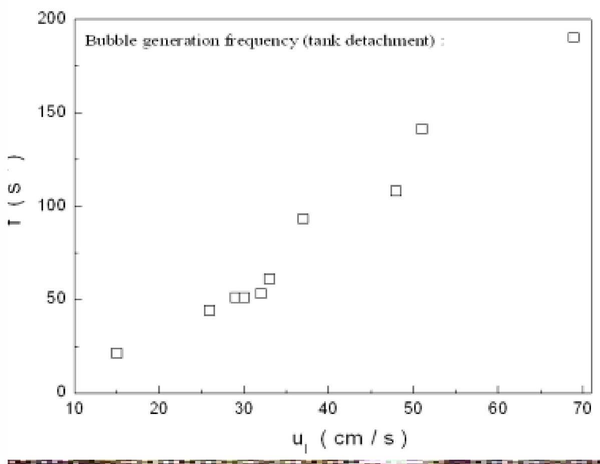
Volumetric flow rates used:
($0.26 \le Q_l \le 1.23$ ml / s, $0.15 \le Q_g \le 0.30$ ml / s)

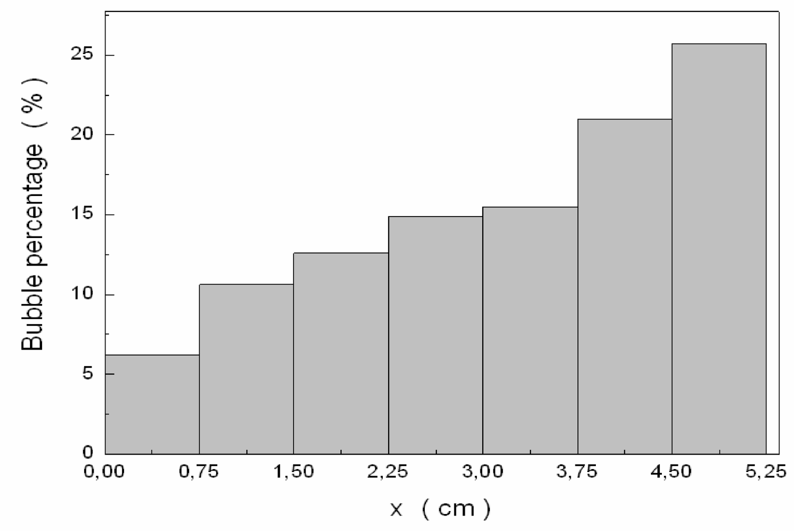
Bremen Drop Tower

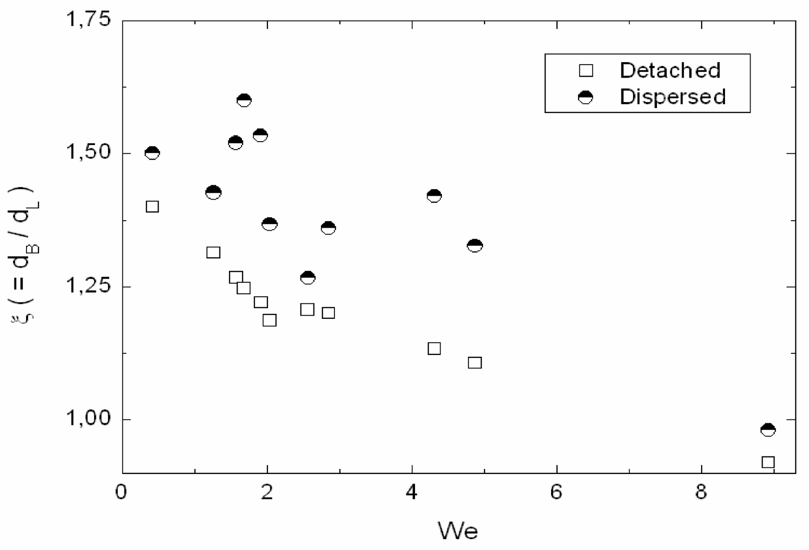
Dropping height =119 m
Compensated gravity time = 4.74 s
Residual accelerations = 10^{-5} to 10^{-6} g_E
Vacuum pressure < 10 Pa
Deceleration levels = 25 - 35 g. (200 ms)











II.- A theoretical study of the dispersion of bubbles in the cavity has been made showing that a qualitative description of the bubble jet which is consistent with experimental observations requires that bubbles differ from being just passive tracers. We introduce a stochastic model for the bubble dispersion in which bubbles are advected passively and, at the same time, dispersed with an effective diffusion coefficient related to the local properties of the turbulent flow, which is modelled by using the RANS k-epsilon model. The probability density of finding a bubble in this stochastic model is governed by a Fokker-Plank type equation. Numerical results seem to show good agreement with the present experimental results.

Dynamics of a bubble suspension in a jet

Bubbles are passive (do not affect significantly the carrying flow)

Bubbles do not follow the streamlines: they spread with an effective diffusivity defined by the local (inhomogeneous) degree of turbulence

Turbulence is quantified, approximately, with k-epsilon model

Standard k-ε model

$$\frac{\partial(\rho k)}{\partial t} + \nabla\cdot(\rho k\mathbf{U}) = \nabla\cdot\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\nabla k\right] + 2\mu_t E_{ij}\cdot E_{ij} - \rho\epsilon$$

$$\frac{\partial(\rho\epsilon)}{\partial t} + \nabla\cdot(\rho\epsilon\mathbf{U}) = \nabla\cdot\left[\left(\mu+\frac{\mu_t}{\sigma_\epsilon}\right)\nabla\epsilon\right] + C_{1\epsilon}\frac{\epsilon}{k}2\mu_t E_{ij}\cdot E_{ij} - C_{2\epsilon}\rho\frac{\epsilon^2}{k}$$

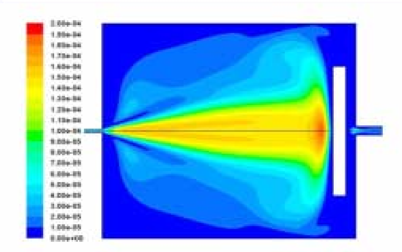
$$\mu_t = \rho C_\mu \frac{k^2}{\epsilon}$$

$$C_\mu = 0.09; \sigma_k = 1.00; \sigma_\epsilon = 1.30; C_{1\epsilon} = 1.44; C_{2\epsilon} = 1.92$$

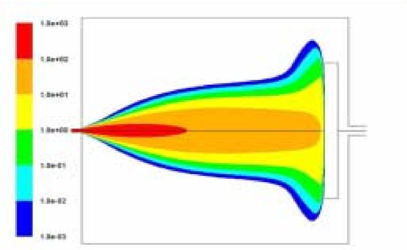
Probability density P of bubbles

$$\frac{\partial P}{\partial t} + \nabla\cdot(\mathbf{U}P) = \nabla\cdot\left[\alpha\frac{k^2}{\epsilon}\nabla P\right]$$ Fokker-Planck description

Model for bubble spreading in jet

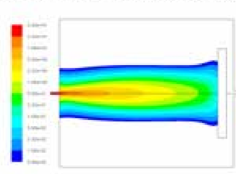


Contours levels of k^2/ϵ for the turbulent jet



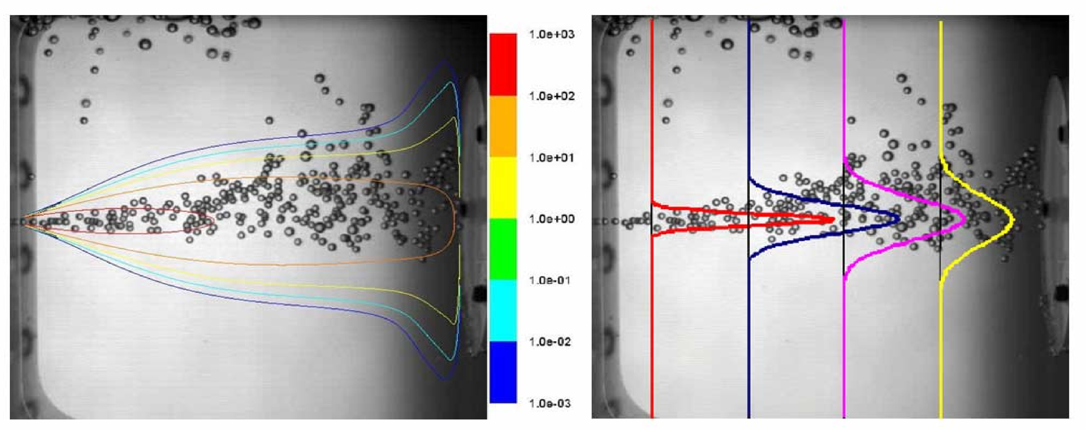
Contour levels of bubble density

Effective diffusivity is highly inhomogeneous!



Case of constant diffusivity

Comparison with Drop Tower experiments



Snapshot of the bubble jet in microgravity after 2 seconds of free fall compared with the contours of probability density

Density profiles at different planes

Inhomogeneous diffusivity is necessary to explain the density profiles

More systematic study will be performed in next campaign of parabolic flights (larger cavity and longer times)

Conclusions

- The performance of the capillary T-junction injector is excellent
- Bubbles of prescribed size and essentially monodisperse can be obtained
- A simple theory explains the performance of the method, and predicts the outcome
- The collective dynamics of a bubble suspension in a jet can be studied
- Little degree of coalescence is found
- A model of inhomogeneous bubble diffusion based on local turbulence explains the observed bubble density profile

[1].- J. Carrera, X. Ruiz, L. Ramírez-Piscina, J. Casademunt, M. Dreyer, *Generation of a Monodisperse Microbubble Jet in Microgravity*, AIAA Journal, Submitted (2007).

[2].- P. Bitlloch, J. Carrera, X. Ruiz, R. González-Cinca, L. Ramírez-Piscina, J. Casademunt, *Numerical Study of the Generation and Dispersion of a Bubble Jet in Microgravity*, 57th International Astronautical Congress, Valencia, September 2006. (IAC-06-A2.P.2 Paper).